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Influence of Amount and Arrangement of Reinforcement on the Mechanism of Destruction of the Corner Part of a Slab-Column Structure

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Abstract

The paper presents results of laboratory investigations concerning a nine field slab-column structure in the scale 1:2. As a model served a reinforced concrete slab with the dimensions of 9300×9300×100 mm. The aim of the investigations was to determine mechanism of destruction of the corner part of a slab-column structure caused by the removal of the support depending on the applied reinforcement. The paper contains the results of laboratory tests compared with the results of simplified numerical calculations.

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Keywords: reinforced concrete construction; progressive collapse; slab-column structure; emergency stage of structure some general terms; some subject-specific terms.

1. Introduction

Nowadays more and more often slab-column structures are constructed. It is generally known that the resistance of such structures to additional loads is considerably less than that of buildings with walls and column-beam structures. The increasing number of such structures involves growing hazards due to the possible occurrence of accidental loads, such as impacts caused by means of transport, internal explosions of gas or assassinations caused by terrorists. These loads comprise also such factor as the application of materials with lower mechanical parameters. The possibility of the occurrence of emergency situations in slab-column structures caused by the removal of one of the supports may result in its complete destruction or in the formation of a secondary structure.

The aim of the discussed investigations was to observe the development of the destruction of the corner part of a slab-column structure after removal of the support, and also to determine approximately the mechanism of destruction, which would permit to determine the values of the destructive load.

2. Description of the tested model

In order to investigate the behaviour of the corner part of a slab column structure after the removal of a support, the model of an actual structure was applied carried out in the scale 1:2. The tested model was a nine-field reinforced concrete slab with the dimensions 9300×9300×100 mm, that supported articulately on 16 columns. The model was divided into parts with different reinforcements (Figs 2, 3).

As the preliminary situation for calculations, in Model I the spacing of the bottom reinforcements in the span band was assumed to be 200 mm. Then, basing on simplified static-strength calculations, approximately the amount of the bottom and upper reinforcement in the other bands was determined. As the next step, the determined amount of reinforcement was

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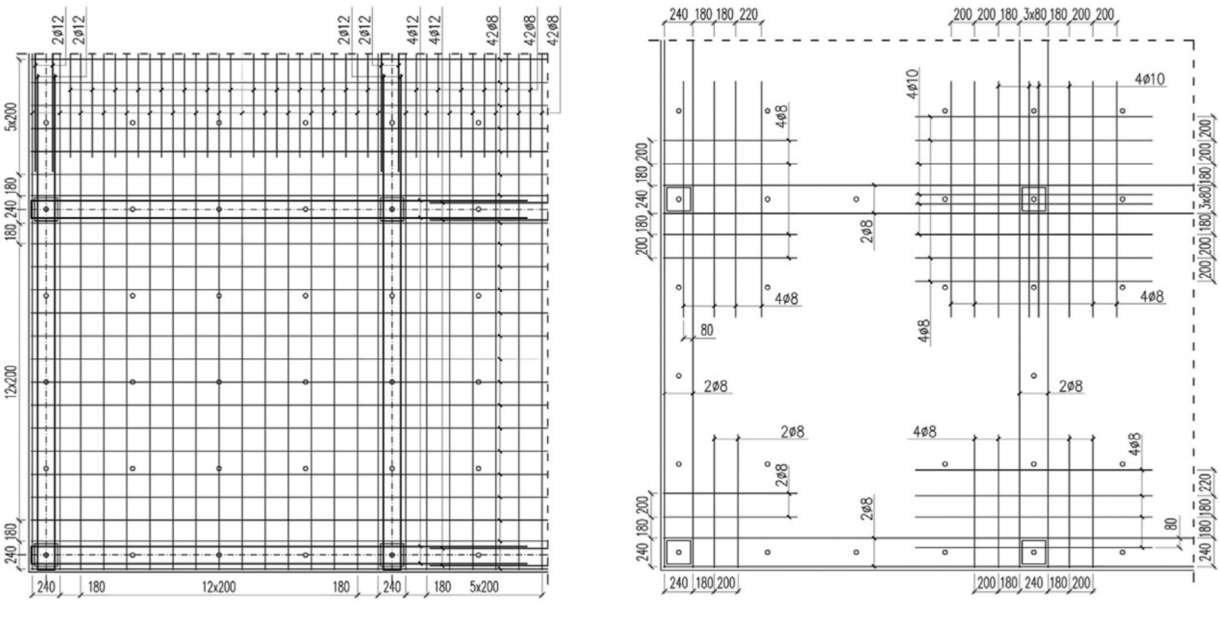
increased by adding a peripheral ties and internal ties as required by EC1 (2010) and taking applying additional reinforcing bars in order to satisfy the conditions of spacing quoted in the standard. This arrangement of the reinforcement in Model 1 was later modified in Model 2 by doubling the amount of upper reinforcement of the support while maintaining an identical bottom reinforcement.

3. 2. Test stand

3.1. Supporting system of the model

The test stand consisted of sixteen prefabricated supports with a height of 2400 mm, which were affirmed to the slab of the laboratory. On these supports the dynamometers for the measurement of reactions of support were imbedded in specially prepared clamping. In the place in which the loss of support was simulated, instead of a prefabricated reinforced concrete the hydraulic cylinder with a large extension was applied. During the investigations, both the model and the test stand were stiffened by steel braces. A view of this model and of the test stand is to be seen in Fig. 1.

Fig. 1. View of the model and test stand



(a)

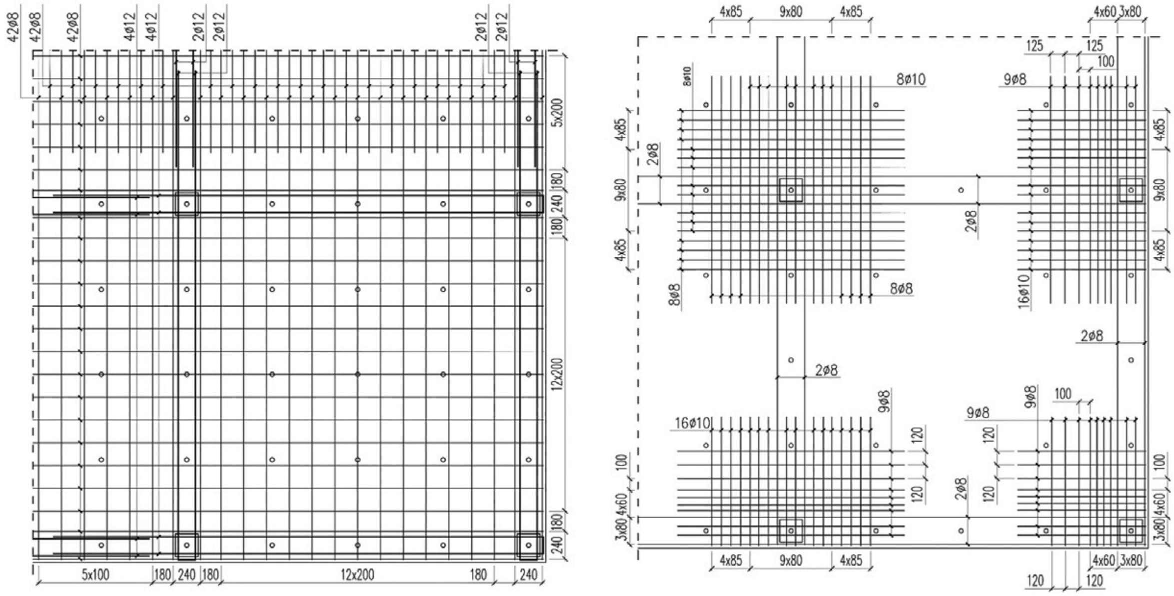
(b)

Fig. 2. Main reinforcement of the Model 1: (a) bottom reinforcement; (b) upper reinforcement

3.2. The system of imposing the load on the model

The load imposed on each model consisted of four mutually independent systems of loads, the distribution of which has been presented in Fig. 4:

- the system of gravitational load (the gravitational load F was realised by means of concrete weights with a mass of 200 kg suspended at 152 points), see Fig. 6;
- an external system of hydraulic load (the hydraulic load H1 consisted of a set of 12 hydraulic cylinders), see Fig. 5a;



(a) (b)

Fig. 3. Main reinforcement of the Model 2: (a) bottom reinforcement; (b) upper reinforcement

- an internal system of hydraulic load (the hydraulic load H2 consisted of a set of nine hydraulic cylinders), e.g. Fig. 5a;
- the hydraulic system supporting the corner part of the model (the hydraulic load H3 was a hydraulic cylinder with a nominal range extension of 1200 mm and a load capacity of 150T, see Fig. 5b.

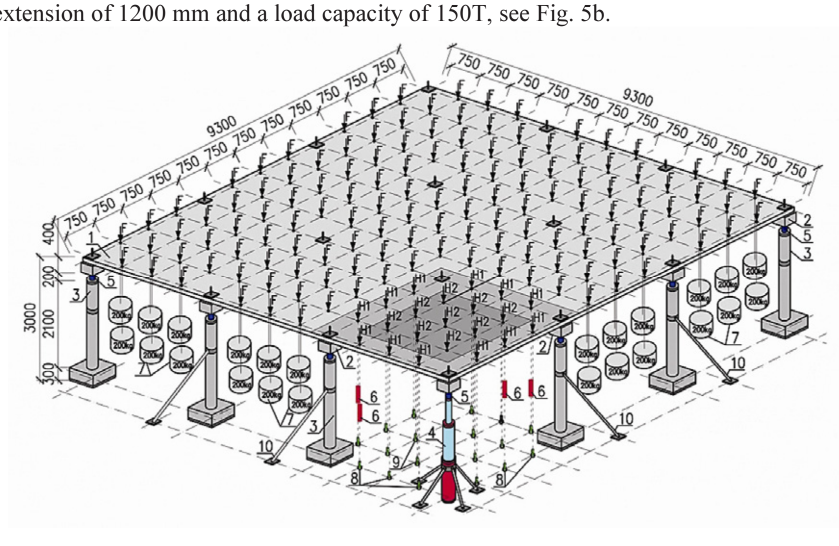


Fig. 4. Isometric view of the test stand and the model [1]: 1 – tested model, 2 – prefabricated support 400 mm high, 3 – prefabricated column support 2,4 m high, 4 – hydraulic cylinders (H3), 5 – dynamometers measuring the reactions of the supports, 6 – dynamometers measuring the loads, 7 – concrete weights with a mass of 200 kg, 8 – a set of 12 hydraulic cylinders (H1), 9 – a set of 9 hydraulic cylinders (H2); 10 – steel braces stabilizing the columns, 20 – steel fittings stabilizing the hydraulic cylinder (H3)

3.3. The system of measurements

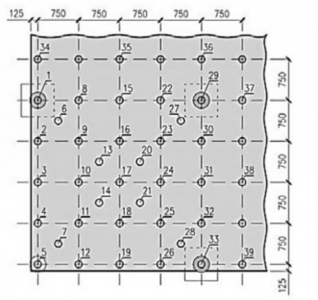
In the course of investigations automatic measurements were performed concerning:

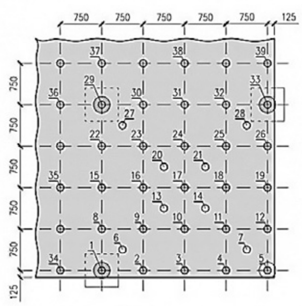
- the values of loads, independently of each set of hydraulic cylinders H1 and H2 by means of dynamometers
- the values of the reaction of the support, for which purpose 16 dynamometers were used,
- the values of vertical displacements of the upper surface of the model, using for this purpose 48 inductive sensors, spaced as show in Figure 7.

(a)  (b) 

Fig. 5. System of hydraulic load: (a) load H1-H2; (b) load H3

Fig. 6. System of gravitational load





(a) (b)

Fig. 7. Distribution of the inductive sensors: (a) Model 1; (b) Model 2

4. Materials

For the reinforcement of the models various type of steel were used both with respect to the diameter and its grade. The steel was tested on sample of rough bars, obtaining for each kind of bars diagrams of the relation σ-ε. Investigation concerning the materials proved that all the bars satisfied the requirements of the grade C according to EC2 (1,15 < ftk/fyk < 1,35). The results of these tests have been presented in table 1.

The models were constructed of normal concrete based on slag cement and aggregate with a maximum diameter of the grains amounting to 8 mm. The material was always tested on the day on which the model was to be investigated, as recommended in PN-EN 12390-3:2002. Table 2 contains the mean values of the mechanical parameters, which were always determined on six samples.

Table 1. Mechanical parameters of rough bars, tested in compliance with PN-EN 10002-1:1998

Diameter of the bar, [mm]	Module of elasticity E, [GPa]	Yield strength f_{yk}, [MPa]	Tensile strength f_{tk}, [MPa]	Total elongation at maximum force ε_{uk}, [%]
8	191,852	526,8	604,4	14,91
10	199,138	561,1	625,8	13,8
12	199,242	601,2	714,2	11,8

Table 2. Mechanical parameters of concrete investigated in compliance with PN-EN 12390-3:2002

Module of elasticity E_{cm}, [GPa]	Compressive Strength $f_{c,cyl}$, [MPa]	Compressive Strength $f_{c,cube}$, [MPa]	Tensile strength f_{cm}, [MPa]
41,2	64,2	79,5	4,07

5. Procedure of investigations

First, before proceeding to tests, the dynamometers measuring the value of the reactions of the supports had to be calibrated. Then the values of these reactions were read off, basing on which the entire mass of the model, including the steel fittings, was determined (mass of the model: 22834 kg, mass of the model without the steel fitting: 20832 kg).

In the first stage of investigations gravitation loads were suspended from the model at 132 points, consisting of concrete loads (Fig. 6). After each of suspended weight the value of the support reactions was read. Next, the vertical displacements of the upper surface of the respective models were measured. In the second stage to each model (Model 1 and Model 2) a preliminary load was imposed the values of which amounted to 2 kN for system H1 and 1 kN for system H2 (Fig. 5a). Next the reactions of the supports and the displacements of the upper surface of the given model were read off. In the third stage of investigations the corner support was lowered at the preset value of the load. The fourth stage consisted in a stepwise increasing of the value of the load (H1/H2=2) up to the moment of the complete destruction of the model, which occurred at a load of 9 kN in the case of Model 1 and 23 kN in the case of Model 2.

6. Result of investigations

6.1. Description of the process of destruction

In the course of the investigations considerably differing mechanisms of destruction have been detected, as well as different values of the destructive load in both models. Model 1 had been assumed to contain less reinforcement than Model 2, but still satisfying all the requirements of the standards. The investigations were started by suspending the gravitation loads spaced 750 mm from each other (132 loads each of them weighing 200 kg). As the second step in the tested field also pointwise loads of 2 kN (~200 kg) were applied by means of hydraulic cylinders. In compliance with the assumed methology the zero readout was performed, after which the model was loaded with increase loads until it was completely destroyed. The first cracks appeared on the upper surface in the supporting zone at a load of 3 kN. At 5 kN there appeared the first cracks indicating the possibility of destruction according to the “classical cantilever scheme” (Fig. 8a), which at a load with the force of 6 kN developed into one single cracking Next, at a load of 7 kN the concrete began crumble along the line between the supports at the corners, and at a load of 9 kN this process transformed itself into a cantilever destruction of the model, see Fig. 8b.

Model 2, characterized by twice as large amount of reinforcement of the supports, was loaded analogically as Model 1. The first cracks turned up in the bottom part of the model, similarly as in the case of Model 1 at a load of 5 kN. Next at 6 kN the first crack appeared on the upper surface of the supporting zone. With the increase in the load, the phenomenon of the coating camber of model progressed. It was visible due to the growing number and width of the cracks parallel to the diaconal passing through the not supported corner. Simultaneously the extension of cracks above the support were visible. Also between the edge supports, cracks were formed on the upper surface of the model in the shape of arcs. The main cracking, shaped like an arc, along which the destruction of the model took place, appeared at the load of 9 kN, see Fig. 8c. At 11 kN the model began to crash at the ends of the bars in the upper supporting reinforcement. The final destruction happened when the load amounted to 22 kN, see Fig. 8d. The views of destroyed corner parts of the slabs are to be seen in Fig. 8.

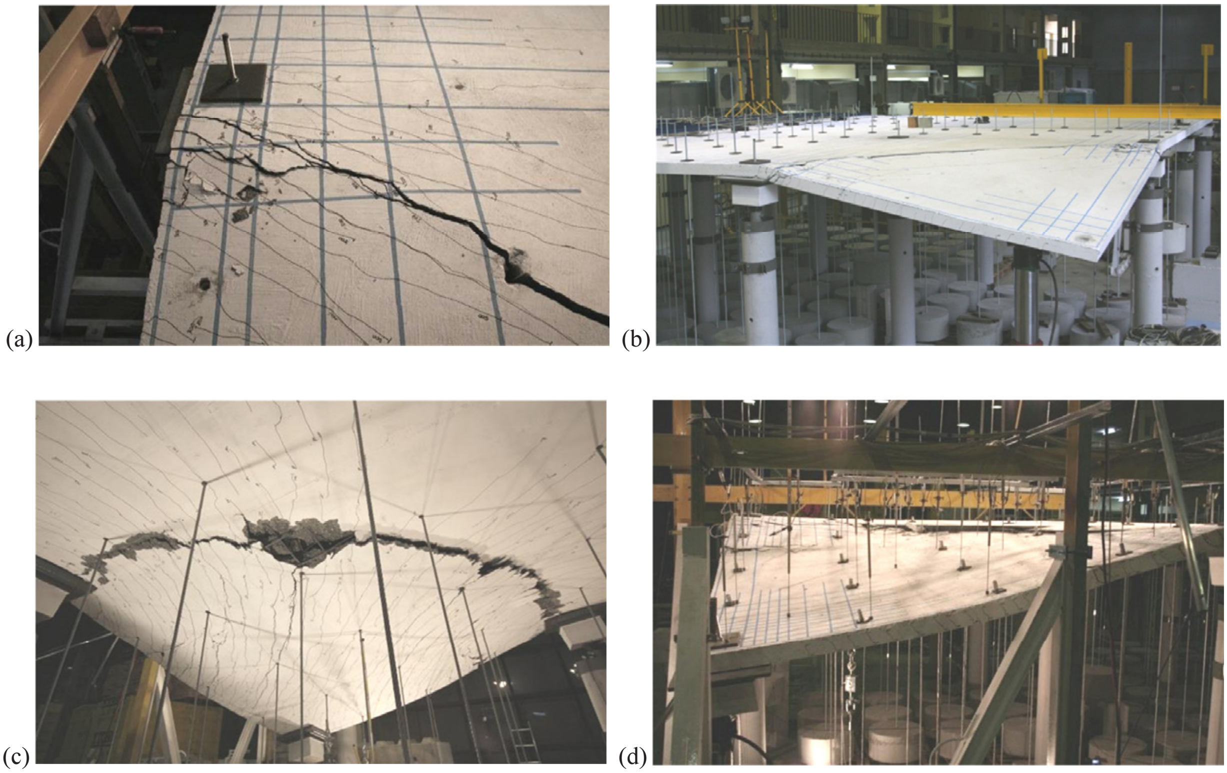


Fig. 8. The stages of the appearance of destructions (dealt with in the text)

6.2. Deformation of the models

Of much importance in the course of these investigations were measurements of displacements at those points the spacing of which, illustrated in Fig. 7, permitted to plot the shape of the surface of the model in each step applying loads. Fig. 9 shows the displacements of the upper surfaces of the investigated models previous to their destruction.

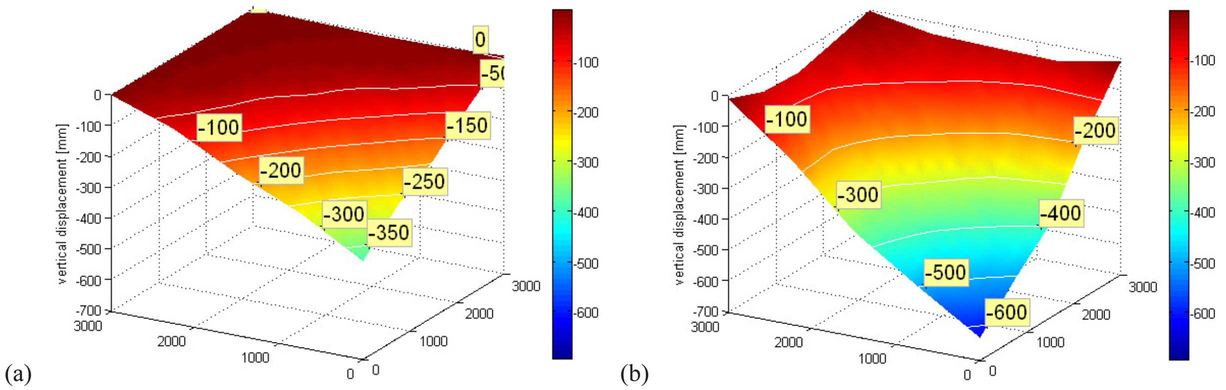


Fig. 9. Displacements of the upper surfaces of the models (results of laboratory tests): (a) Model 1; (b) Model 2

7. Numerical calculations

In order to describe in more detail the mechanisms of destruction in the course of laboratory tests, attempts have been made to compare the obtained results of displacement of the upper surface of the slab with those obtained in numerical calculations, in which the simple engineering programme “ABC Slab” was used, whose algorithms of calculations are based on formulae quoted in the standard EC2 (2010). In these calculations it was assumed that:

- the values concerning the thickness of the model and its dimensions coincide with those of the actual model,
- the scheme of the load of each model consisted of:
    - a constant load (the dead load of the model) – distributed uniformly load,
    - a varying load (hydraulic load) – concentrated load.

While constructing the models, the effect of damages in the areas adjacent to the considered one and resulting from destructions occurring during investigations of previous models, have not been taken into account. The values of displacements obtained in laboratory tests and those obtained in numerical calculations have been given in Fig. 10.

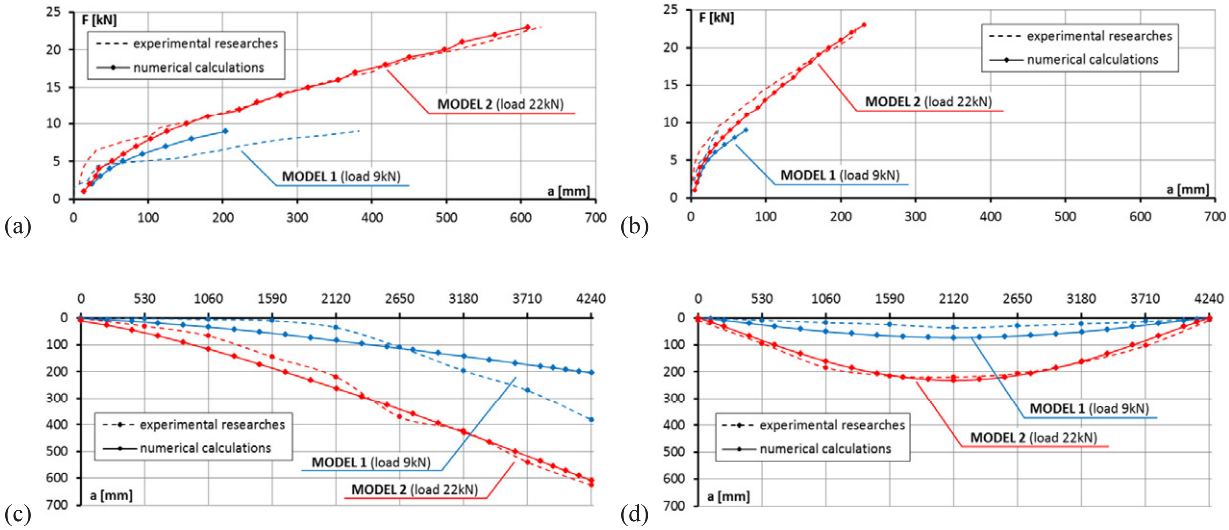


Fig. 10. Displacements of the upper surfaces of the models (results of laboratory tests and numerical calculations): (a) displacement at the end of the corner; (b) displacement in the centre of the field; (c) displacements along the diagonal between the edge columns; (d) displacements along the diagonal without a column.

8. Analysis of the results

Considerable differences between the values of displacements obtained result in the tests, and the results of numerical investigations (Fig. 10), among others, from simplifications applied in the program of calculations (orthotropic thin slab with small deflection). The algorithms of this program are based on standard formulae quoted in EC2 (2010). The application of the algorithm of calculations assumed in the standard imposes the shape of the deformation due to the rigidity of all the finite elements of the model. The assumption of the model is, however, correct only when the given element displays considerable cracking. In fact, in the course of investigations applying modest loads, slight cracks may turn up at a large distance, which then slowly get larger. Basing on the obtained results (Fig. 10) we may conclude that:

- the applied programme managed to image rather accurately the phenomenon of the formation of a concave coating, observed during the test, in spite of the fact that the programme did not assume a situation with large displacements can be calculated,
- the obtained differences of the deflection in Model 2 within the assumed range of the load, both at the corner and in the centre of the slab, are contained in the range of values ± 20%, because in the final zone of the load the differences do not excess 5%,
- the deflections obtained in Model 1 result from its destruction due to the typical cantilever scheme of destruction, differing considerably from the diagram obtained basing on numerical calculations. In the investigations, in the case of the destruction by the cantilever scheme, the sagging part was a flat plane, whereas in the numerical model a reversed coat was formed, although not a considerable camber.

The diagrams presented in Figure 10, illustrating the displacements of the upper surfaces of the models along the diagonals indicate that the observed scheme of destruction concerning Model 2 differs considerably from the mechanisms of destruction preliminarily assumed. Due to the loss of the support at the corner, the surface of the slab assumed the shape of a concave coat, though not a very high one. At the moment of its destruction the deflection proved to amount to about 220 mm (Model 2), the thickness of the model amounting to 100 mm. This change of the shape of the element in the cross-section between the edge columns increased considerably the arm of internal forces, leading, among others, to a much higher load capacity of the model than had been expected. Such large displacements, obtained in laboratory tests and calculations indicate a change in the character of the behaviour of the corner part of the slab-column structure from the slab to the shell character. This permitted to achieve a 2,66 times higher value of the destructive load (Model 1: H1=9 kN, Model 2: H1=24 kN). In Model 1, despite the occurrence of an identical situation of the sagging of the field in its very centre by about 35 mm, the destruction proceeded in compliance with the predicted cantilever scheme.

9. Conclusions

The performed investigations and their analysis permit to draw the following conclusions.

- The scheme of the slab-column structure of the last storey supported in one point applied in calculations of the investigated model, was selectees as being the most unfavourable scheme of the behaviour of the structure. Actually, in the case of a lost the column according to the recommendations quoted in EC1 concerning the construction of the peripheral ties, the internal ties, the horizontal ties and the vertical ties, the intermediate storey and last storey will be situated most favourably.
- The application of a 100%, surplus of supporting reinforcement in the extreme band exceeding the results obtained by means of standard calculations permitted to gain in the investigated corner parts of the secondary structure a reversed shell, thanks to which a much higher load capacity of the damaged part could be achieved. The obtained mechanism of behaviour of the corner part after the removal of the support proved to be surprising differs from the mechanisms applied in the classical approach to this problem. This paper presents merely some part of the results of our investigations. They lead to the conclusion that the effect of a concave shell can already achieved at 20% of the surplus of the upper reinforcement in the edge band.
- The considerable coincidence of displacements in calculations carried out in compliance with the engineering programme and investigations, achieved in the range of large displacements and loads, indicates the possibility of applying this tool in the assessment of displacements of the corner parts of slab-columns structures after the removal of the support.
- The considerable reserves of the load capacity, resulting from changes in the character of the behaviour of the given element, detected in the course of investigations, may probably occur in actual structures only when we have to do with an adequately arranged reinforcement in the roof and a considerable ductility of the reinforcing steel.

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